Biosolids Application to No-Till Dryland Rotations: 2012 Results
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INTRODUCTION

Biosolids recycling on dryland winter wheat (*Triticum aestivum*, L.) can supply a reliable, slow-release source of nitrogen (N) (Barbarick et al., 1992). Barbarick and Ippolito (2000, 2007) found that continuous application of biosolids from the Littleton/Englewood, CO wastewater treatment facility to dryland winter wheat-fallow rotation provides about 16 lbs N per dry ton. This research involved tilling the biosolids into the top 8 inches of soil. A new question related to soil management in a biosolids beneficial-use program is: How much N would be available if the biosolids were surface-applied in a no-till dryland agroecosystem with winter wheat-fallow (WF) and winter wheat-corn (*Zea mays*, L.)-fallow (WCF) crop rotations?

Our objective was to compare agronomic rates of commercial N fertilizer to an equivalent rate of biosolids in combination with WF and WCF crop rotations. Our hypotheses were that biosolids addition, compared to N fertilizer, would:

1. Produce similar crop yields;
2. Not differ in grain P, Zn, and Cu levels.
3. Not differ in soil P, Zn, and Cu AB-DTPA extractable concentrations, a measure of plant availability (Barbarick and Workman, 1987); and
4. Not affect soil salinity (electrical conductivity of saturated soil-paste extract, EC), pH or soil accumulation of nitrate-N (NO$_3$-N).

MATERIALS AND METHODS

In 1999, we established our research on land owned by the Cities of Littleton and Englewood (L/E) in eastern Adams County, approximately 28 miles east of Byers, CO. The latitude longitude for the plot corners are 39°45’47”/103°47”50” (southwest), 39°45’47”/103°47”17” (southeast), 39°46’7”/103°47”50” (northwest), 39°46’7”/103°47”17” (northeast). The Linnebur family manages the farming operations for L/E. Soils belong to the Adena-Colby association where the Adena soil is classified as an Ustollic Paleargid and Colby is classified as an Ustic Torriorthent. No-till management is used in conjunction with crop rotations of WF and WCF. We originally also used a wheat-wheat-corn-sunflower (*Helianthus annuus*, L.)-fallow rotation. After the 2004 growing season, we abandoned this rotation because of persistent droughty conditions that restricted sunflower production.

We installed a Campbell Scientific weather station at the site in April 2000; Tables 1 and 2 present mean temperature and precipitation data, and growing season precipitation, respectively.

The first biosolids application occurred in August 1999. Planting sequences are given in Table 3. We used a randomized complete block design with four blocks. Each phase of each rotation was present every year. Each plot was 100 feet wide by approximately 0.5 mile (2640...
feet) long. The width of each plot was split so that one 50-foot wide section received commercial N fertilizer applied with the seed and sidedressed after plant establishment (Table 3), and the second 50-foot wide section received biosolids applied by L/E with a manure spreader. We randomly selected which half of the strip in each rotation received N fertilizer or biosolids. Characteristics of the L/E biosolids are provided in Table 4. The N fertilizer and biosolids applications were based on soil test recommendations determined on each plot before planting each crop. The Cities of L/E completed biosolids application for wheat in August 1999, 2001, 2003, and 2004 and for the summer crops in March 2000, 2001, 2002, 2003, 2004, 2005, and 2012. We planted the first corn crop in May 2000. We also established wheat rotations in September 2000 through 2012 and corn rotations in May 2001 through 2012, and sunflower plantings in June 2001, 2002, and 2003. Soil moisture was inadequate in June 2004 to plant sunflowers (see Table 1). The sunflower portion of the study was abandoned in 2004.


Following each harvest, we collected soil samples using a Giddings hydraulic probe. For AB-DTPA extractable Cu, P, and Zn (Barbarick and Workman, 1987) and EC (Rhoades, 1996) and pH (Thomas, 1996), we sampled to one foot and separated the samples into 0-2, 2-4, 4-8, and 8-12 inch depth increments. For soil NO$_3$-N (Mulvaney, 1996) analyses, we sampled to 6 feet and separated the samples into 0-2, 2-4, 4-8, 8-12, 12-24, 24-36, 36-48, 48-60, and 60-72 inch depth increments.

For the wheat rotations, the experimental design was a split-plot design where type of rotation was the main plot and type of nutrient addition (commercial N fertilizer versus L/E biosolids) was the subplot. For crop yields and soil-sample analyses, main plot effects, subplot effects, and interactions were tested for significance using least significant difference (LSD) at the 0.10 probability level. Since we only had one corn rotation, we could only compare the commercial N versus L/E biosolids using a “t” test at the 0.10 probability level.
RESULTS AND DISCUSSION

Precipitation Data


2012 Crop Grain Data

No significant wheat (Figure 1) or corn yield (Table 5) differences were found for type of rotation or nutrient source. Average wheat yield for our treatments was 45 bushels/acre while the Colorado state average was 46 bushels/acre (USDA NASS Colorado Field Office, 2012). The corn yields indicate a near crop failure. Only 3.8 inches of rain were received during the corn growing season (Table 2).

The rotation by nutrient source interaction affected the wheat grain P and Zn content with the highest concentrations found in the WF rotation that received biosolids (Figures 3 and 4). The nitrogen fertilizer treatment increased corn-grain Cu compared the biosolids treatment (Table 5).

2012 Soil Data

In the wheat plots, several rotation effects and rotation by nutrient source interactions were found for ABDTPA P, Zn, and Cu and for EC and NO$_3$-N (Figures 5-10); however, no consistent trend with soil depth was noted. Biosolids application led to larger ABDTPA Cu concentrations in the top 4 inches of soil and larger salt content (EC) in the top 2 inches.

In the CFW rotation, we found that the biosolids produced higher ABDTPA P, Zn, and Cu in the top 2 inches and ABDTPA P in the 2 to 4 inch depth (Table 6). We expected this result since the biosolids were surface applied and not incorporated. Biosolids also led to higher levels of NO$_3$-N in the 0 to 2, 2 to 4, 36 to 48, 48 to 60, and 60 to 72 inch depths.
CONCLUSIONS

Relative to our hypotheses listed on page 3, we found the following trends:

1. In the 2012 wheat and corn plots, we observed that biosolids did not significantly increase yields or grain concentrations of protein, P, Zn, and Cu compared to N fertilizer.

2. For dryland wheat in 2012, we observed that biosolids additions did increase some soil levels of ABDTPA-extractable P, Zn, Cu, and soil NO₃-N concentrations.

3. We found that biosolids application did produce higher soil salinity (EC) levels in the top 2 inches in the wheat plots as compared to N fertilizer applications. No consistent trends were found for soil pH.

4. We applied biosolids to the 2012-13 wheat plots.
REFERENCES


Table 1. Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2011. (Weather station was installed in April, 2000).

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Table 1 (continued). Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2011. (Weather station was installed in April, 2000).

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* We installed the weather station in mid-April, 2000. The tipping bucket rain gauge may not accurately measure precipitation received as snow.
Table 2. Growing season precipitation.

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Table 3. Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2009.

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<td>15</td>
</tr>
<tr>
<td>2000</td>
<td>June</td>
<td>Sunflowers</td>
<td>Triumph 765, 766 (confection type)</td>
<td>2</td>
<td>32</td>
<td>5</td>
<td>40</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>2000</td>
<td>9/25/00</td>
<td>Wheat</td>
<td>Prairie Red</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>20</td>
</tr>
<tr>
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<td>5/11/01</td>
<td>Corn</td>
<td>Pioneer 37M81</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>15</td>
</tr>
<tr>
<td>2001</td>
<td>6/20/01</td>
<td>Sunflowers</td>
<td>Triumph 545A</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>15</td>
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<tr>
<td>2001</td>
<td>09/17/01</td>
<td>Wheat</td>
<td>Prairie Red</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>20</td>
</tr>
<tr>
<td>2002</td>
<td>5/11/01</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>15</td>
</tr>
<tr>
<td>2002</td>
<td>6/28/03</td>
<td>Sunflowers</td>
<td>Stanton</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>20</td>
</tr>
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<td>2003</td>
<td>5/10/05</td>
<td>Corn</td>
<td>Triumph 9066</td>
<td>Variable</td>
<td>Variable</td>
<td>5</td>
<td>Variable</td>
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Table 3.  (continued) Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2009.

<table>
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<tr>
<th>Year</th>
<th>Month</th>
<th>Crop</th>
<th>Variety</th>
<th>Biosolids</th>
<th>Fertilizer</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2007</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2007</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2008</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2008</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2009</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2009</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Yumar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2011</td>
<td>May</td>
<td>Corn</td>
<td>Pioneer J99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2011</td>
<td>Sept.</td>
<td>Wheat</td>
<td>Snowmass</td>
<td>2</td>
<td>32</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>2012</td>
<td>May</td>
<td>Corn</td>
<td>Triumph 9958</td>
<td>2</td>
<td>32</td>
<td>5</td>
<td>30</td>
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Table 4. Littleton/Englewood biosolids composition used at the Byers research site, 1999-2012.

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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Solids, g kg⁻¹</td>
<td>217</td>
<td>---</td>
<td>210</td>
<td>220</td>
<td>254</td>
<td>192</td>
<td>197</td>
<td>211</td>
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<td>pH</td>
<td>7.6</td>
<td>7.8</td>
<td>8.4</td>
<td>8.1</td>
<td>8.5</td>
<td>8.2</td>
<td>8.8</td>
<td>8.2</td>
</tr>
<tr>
<td>EC, dS m⁻¹</td>
<td>6.2</td>
<td>11.2</td>
<td>10.6</td>
<td>8.7</td>
<td>7.6</td>
<td>7.4</td>
<td>4.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Org. N, g kg⁻¹</td>
<td>50</td>
<td>47</td>
<td>58</td>
<td>39</td>
<td>54</td>
<td>46</td>
<td>43</td>
<td>38</td>
</tr>
<tr>
<td>NH₄-N, g kg⁻¹</td>
<td>12</td>
<td>7</td>
<td>14</td>
<td>16</td>
<td>9</td>
<td>13</td>
<td>14</td>
<td>14</td>
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<tr>
<td>NO₃-N, g kg⁻¹</td>
<td>0.023</td>
<td>0.068</td>
<td>0.020</td>
<td>0.021</td>
<td>0.027</td>
<td>0.016</td>
<td>0.010</td>
<td>0</td>
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<td>K, g kg⁻¹</td>
<td>5.1</td>
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<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
<td>2.6</td>
<td>2.1</td>
<td>1.7</td>
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<tr>
<td>P, g kg⁻¹</td>
<td>29</td>
<td>18</td>
<td>34</td>
<td>32</td>
<td>26</td>
<td>28</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td>Al, g kg⁻¹</td>
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<td>18</td>
<td>15</td>
<td>18</td>
<td>14</td>
<td>15</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Fe, g kg⁻¹</td>
<td>31</td>
<td>22</td>
<td>34</td>
<td>33</td>
<td>23</td>
<td>24</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Cu, mg kg⁻¹</td>
<td>560</td>
<td>820</td>
<td>650</td>
<td>750</td>
<td>596</td>
<td>689</td>
<td>696</td>
<td>611</td>
</tr>
<tr>
<td>Zn, mg kg⁻¹</td>
<td>410</td>
<td>543</td>
<td>710</td>
<td>770</td>
<td>506</td>
<td>629</td>
<td>676</td>
<td>716</td>
</tr>
<tr>
<td>Ni, mg kg⁻¹</td>
<td>22</td>
<td>6</td>
<td>11</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Mo, mg kg⁻¹</td>
<td>19</td>
<td>22</td>
<td>36</td>
<td>17</td>
<td>21</td>
<td>34</td>
<td>21</td>
<td>13</td>
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<tr>
<td>Cd, mg kg⁻¹</td>
<td>6.2</td>
<td>2.6</td>
<td>1.6</td>
<td>1.5</td>
<td>1.5</td>
<td>2.2</td>
<td>4.2</td>
<td>2.0</td>
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<tr>
<td>Cr, mg kg⁻¹</td>
<td>44</td>
<td>17</td>
<td>17</td>
<td>13</td>
<td>9</td>
<td>14</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Pb, mg kg⁻¹</td>
<td>43</td>
<td>17</td>
<td>16</td>
<td>18</td>
<td>15</td>
<td>21</td>
<td>26</td>
<td>16</td>
</tr>
<tr>
<td>As, mg kg⁻¹</td>
<td>5.5</td>
<td>2.6</td>
<td>1.4</td>
<td>3.8</td>
<td>1.4</td>
<td>1.6</td>
<td>0.5</td>
<td>0.05</td>
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<td>Se, mg kg⁻¹</td>
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<td>16</td>
<td>7</td>
<td>6</td>
<td>17</td>
<td>1</td>
<td>3</td>
<td>0.07</td>
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<tr>
<td>Hg, mg kg⁻¹</td>
<td>3.4</td>
<td>0.5</td>
<td>2.6</td>
<td>2.0</td>
<td>1.1</td>
<td>0.4</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Ag, mg kg⁻¹</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>15</td>
<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>Ba, mg kg⁻¹</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>533</td>
<td>7</td>
</tr>
<tr>
<td>Be, mg kg⁻¹</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.05</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mn, mg kg⁻¹</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>239</td>
<td>199</td>
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</table>
Table 4 (continued). Littleton/Englewood biosolids composition used at the Byers research site, 1999-2012.

<table>
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<tr>
<th>Parameter</th>
<th>2012 Corn</th>
<th>Avg.</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Solids, g kg(^{-1})</td>
<td>170</td>
<td>208</td>
<td>170-254</td>
</tr>
<tr>
<td>pH</td>
<td>8.7</td>
<td>8.3</td>
<td>7.6-8.8</td>
</tr>
<tr>
<td>EC, dS m(^{-1})</td>
<td>3.5</td>
<td>7.2</td>
<td>3.5-11.2</td>
</tr>
<tr>
<td>Org. N, g kg(^{-1})</td>
<td>12</td>
<td>43</td>
<td>12-58</td>
</tr>
<tr>
<td>NH(_4)-N, g kg(^{-1})</td>
<td>2</td>
<td>11</td>
<td>2-16</td>
</tr>
<tr>
<td>NO(_3)-N, g kg(^{-1})</td>
<td>0.003</td>
<td>0.021</td>
<td>0.0068</td>
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<td>K, g kg(^{-1})</td>
<td>0.3</td>
<td>2.3</td>
<td>0.3-5.1</td>
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<tr>
<td>P, g kg(^{-1})</td>
<td>5</td>
<td>24</td>
<td>5-34</td>
</tr>
<tr>
<td>Al, g kg(^{-1})</td>
<td>1</td>
<td>15</td>
<td>1-28</td>
</tr>
<tr>
<td>Fe, g kg(^{-1})</td>
<td>4</td>
<td>24</td>
<td>4-34</td>
</tr>
<tr>
<td>Cu, mg kg(^{-1})</td>
<td>138</td>
<td>613</td>
<td>138-820</td>
</tr>
<tr>
<td>Zn, mg kg(^{-1})</td>
<td>140</td>
<td>567</td>
<td>140-770</td>
</tr>
<tr>
<td>Ni, mg kg(^{-1})</td>
<td>4</td>
<td>10</td>
<td>4-22</td>
</tr>
<tr>
<td>Mo, mg kg(^{-1})</td>
<td>2</td>
<td>10</td>
<td>2-36</td>
</tr>
<tr>
<td>Cd, mg kg(^{-1})</td>
<td>0.2</td>
<td>2.4</td>
<td>0.2-6.2</td>
</tr>
<tr>
<td>Cr, mg kg(^{-1})</td>
<td>2</td>
<td>16</td>
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<tr>
<td>Pb, mg kg(^{-1})</td>
<td>6</td>
<td>10</td>
<td>6-43</td>
</tr>
<tr>
<td>As, mg kg(^{-1})</td>
<td>2.0</td>
<td>1.2</td>
<td>0.05-5.5</td>
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<tr>
<td>Se, mg kg(^{-1})</td>
<td>12</td>
<td>9</td>
<td>0.07-20</td>
</tr>
<tr>
<td>Hg, mg kg(^{-1})</td>
<td>0.01</td>
<td>1.2</td>
<td>0.01-3.4</td>
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<tr>
<td>Ag, mg kg(^{-1})</td>
<td>3.5</td>
<td>4.9</td>
<td>0.5-15</td>
</tr>
<tr>
<td>Ba, mg kg(^{-1})</td>
<td>76</td>
<td>205</td>
<td>7-533</td>
</tr>
<tr>
<td>Be, mg kg(^{-1})</td>
<td>&lt;0.01</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Mn, mg kg(^{-1})</td>
<td>73</td>
<td>170</td>
<td>73-239</td>
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Table 5. Corn grain characteristics for the corn rotation (CFW) at the Byers research site for 2012. **Highlighted parameters** are significant at the 0.10 probability level.

<table>
<thead>
<tr>
<th>Parameter, units</th>
<th>Biosolids</th>
<th>Nitrogen</th>
<th>Probability level</th>
</tr>
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<tbody>
<tr>
<td>Yield, bushels/acre</td>
<td>12</td>
<td>16</td>
<td>0.373</td>
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<tr>
<td>Protein, %</td>
<td>12.1</td>
<td>12.2</td>
<td>0.444</td>
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<tr>
<td>P, g/kg</td>
<td>6.0</td>
<td>6.1</td>
<td>0.888</td>
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<tr>
<td>Zn, mg/kg</td>
<td>32</td>
<td>34</td>
<td>0.393</td>
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<tr>
<td><strong>Cu, mg/kg</strong></td>
<td><strong>3.0</strong></td>
<td><strong>3.3</strong></td>
<td><strong>0.085</strong></td>
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Table 6. Soil characteristics for the corn rotation (CFW) at the Byers research site for 2012. **Highlighted parameters** are significant at the 10% probability level.

<table>
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<th>Parameter, units</th>
<th>Depth, inches</th>
<th>Biosolids</th>
<th>Nitrogen</th>
<th>Probability level</th>
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<tbody>
<tr>
<td><strong>ABDTPA P, mg kg⁻¹</strong></td>
<td>0-2</td>
<td>39.5</td>
<td>14.3</td>
<td><strong>0.008</strong></td>
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<td>9.9</td>
<td>1.8</td>
<td><strong>0.024</strong></td>
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<td>4-8</td>
<td>1.1</td>
<td>0.01</td>
<td>0.164</td>
</tr>
<tr>
<td></td>
<td>8-12</td>
<td>0.8</td>
<td>0.2</td>
<td>0.383</td>
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<td><strong>ABDTPA Zn, mg kg⁻¹</strong></td>
<td>0-2</td>
<td>4.07</td>
<td>0.89</td>
<td><strong>0.006</strong></td>
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<td>2-4</td>
<td>0.35</td>
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<td>4-8</td>
<td>0.20</td>
<td>0.33</td>
<td>0.630</td>
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<td>8-12</td>
<td>0.24</td>
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<td>0.132</td>
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<tr>
<td><strong>ABDTPA Cu, mg kg⁻¹</strong></td>
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<td>7.6</td>
<td>1.8</td>
<td><strong>0.004</strong></td>
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<td>2.0</td>
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<td>7.7</td>
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<td>0.540</td>
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<td>4-8</td>
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<td>0.334</td>
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<td><strong>NO₃-N, mg kg⁻¹</strong></td>
<td>0-2</td>
<td>48.7</td>
<td>17.2</td>
<td><strong>0.063</strong></td>
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<td>2-4</td>
<td>31.8</td>
<td>17.0</td>
<td>0.195</td>
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<td>4-8</td>
<td>15.4</td>
<td>7.7</td>
<td><strong>0.070</strong></td>
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<td>8-12</td>
<td>8.0</td>
<td>4.3</td>
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<td>12-24</td>
<td>13.3</td>
<td>2.2</td>
<td>0.207</td>
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<td>24-36</td>
<td>17.1</td>
<td>1.5</td>
<td>0.293</td>
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<td><strong>36-48</strong></td>
<td><strong>16.1</strong></td>
<td><strong>2.8</strong></td>
<td><strong>0.096</strong></td>
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<td><strong>48-60</strong></td>
<td><strong>24.7</strong></td>
<td><strong>3.0</strong></td>
<td><strong>0.036</strong></td>
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<td><strong>60-72</strong></td>
<td><strong>22.1</strong></td>
<td><strong>3.4</strong></td>
<td><strong>0.023</strong></td>
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Figure 1. Wheat grain yields for 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).
Figure 2. Wheat grain P concentrations for 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).
Figure 3. Wheat grain Zn concentrations for 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, \( \text{LSD}_{0.10} \) represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).
Figure 4. Wheat grain Cu concentrations for 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).
Figure 5. Soil ABDTPA-extractable P concentration following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.

**Statistical summary by soil depth:**

- **0-2 inches**
  - LSD$_{0.10}$
  - Rotations NS
  - Treatment NS
  - Rot. X Treat. NS

- **2-4 inches**
  - LSD$_{0.10}$
  - Rotations NS
  - Treatment NS
  - Rot. X Treat. 2.8

- **4-8 inches**
  - LSD$_{0.10}$
  - Rotations NS
  - Treatment NS
  - Rot. X Treat. NS

- **8-12 inches**
  - LSD$_{0.10}$
  - Rotations NS
  - Treatment NS
  - Rot. X Treat. NS
Figure 6. Soil ABDTPA-extractable Zn concentration following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.
Figure 7. Soil ABDTPA-extractable Cu concentration following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.
Figure 8. Soil saturated-paste electrical conductivity (EC) following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD_{0.10} represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.

Statistical summary by soil depth:

0-2 inches
LSD_{0.10}
Rotations NS
_Treatment 0.05_ Rot. X Treat. NS

2-4 inches
LSD_{0.10}
Rotations NS
_Treatment NS_ Rot. X Treat. NS

4-8 inches
LSD_{0.10}
Rotations NS
_Treatment NS_ Rot. X Treat. NS

8-12 inches
LSD_{0.10}
Rotations NS
_Treatment NS_ Rot. X Treat. NS
Figure 9. Soil saturated-paste pH following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.

Statistical summary by soil depth:

<table>
<thead>
<tr>
<th>Depth, inches</th>
<th>Biosolids</th>
<th>Nitrogen fertilizer</th>
<th>Rotations</th>
<th>Treatment</th>
<th>Rot. X Treat.</th>
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</thead>
<tbody>
<tr>
<td>0-2 inches</td>
<td>LSD$_{0.10}$</td>
<td>Rotations NS</td>
<td>Treatment NS</td>
<td>Rot. X Treat. NS</td>
<td></td>
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<tr>
<td>2-4 inches</td>
<td>LSD$_{0.10}$</td>
<td>Rotations NS</td>
<td>Treatment NS</td>
<td>Rot. X Treat. 0.2</td>
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<tr>
<td>4-8 inches</td>
<td>LSD$_{0.10}$</td>
<td>Rotations 0.4</td>
<td>Treatment NS</td>
<td>Rot. X Treat. NS</td>
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<tr>
<td>8-12 inches</td>
<td>LSD$_{0.10}$</td>
<td>Rotations 0.2</td>
<td>Treatment NS</td>
<td>Rot. X Treat. 0.1</td>
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</table>
Figure 10. Soil NO$_3$-N concentrations following 2012 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD$_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.